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Research on Airflow Pressure Changes in High-Speed Railway Tunnels and Tunnel Structure Optimization

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Abstract. As the operating speed of high-speed trains increases to 300–400 km/h, trains entering enclosed tunnels generate a significant piston effect, producing strong compression and expansion waves. These pressure waves can cause substantial pressure differences between the interior and exterior of the train, thereby reducing passenger comfort. Shock waves at tunnel portals can also generate intense noise and threaten the stability of surrounding slopes. Meanwhile, the substantial increase in aerodynamic resistance leads to higher energy consumption. To address these issues, this study focuses on fundamental fluid mechanics theories, the Navier–Stokes (N–S) equations, one-dimensional pressure-wave propagation, and wave transmission and reflection. Based on these principles, the aerodynamic phenomena occurring throughout the entire process of a train passing through a tunnel are examined, with particular attention to the coupled variations in airflow velocity and pressure. Drawing on these theories and previous tunnel optimization studies conducted in China and abroad, this study summarizes structural optimization approaches for railway tunnels, including tunnel cross-sectional designs and portal buffer structures. The results show that increasing the tunnel clearance and reducing the blockage ratio can weaken air compression when a train enters the tunnel. Gradually varying tunnel portals and buffer hoods can reduce the pressure gradient at the front of the compression wave, while perforated buffer structures can further mitigate micro-pressure waves at the tunnel portal by diverting compressed air. This study can provide a theoretical reference for the aerodynamic design of ultra-high-speed railway tunnels and the standardization of buffer structure design for high-speed railway tunnels.

Keywords: High-speed train, Bernoulli's theorem, Railway tunnel, Pressure gradient, Aerodynamics

1. Introduction

By the end of 2024, the total length of high-speed railways in operation in China had exceeded 48,000 km, with 4,917 high-speed railway tunnels completed [1]. As the operating speed of high-speed railways in China continues to increase, some lines have reached speeds of 350 km/h. Meanwhile, with the continued development of higher-speed railway technologies, the aerodynamic interaction between high-speed trains and the surrounding air has become increasingly significant. Changes in the tunnel boundary experienced during train entry, exit, or abrupt variations in tunnel

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cross-section can initiate compression and expansion waves. These waves can cause ear discomfort in passengers. Changes in the tunnel boundary experienced during train entry, exit, or abrupt variations in tunnel cross-section can initiate compression and expansion waves. This has become a major engineering challenge that needs to be addressed in the aerodynamic design of high-speed railway tunnels [2, 3].

Therefore, understanding the changes in airflow pressure after a high-speed train enters a tunnel and reducing adverse aerodynamic effects through appropriate tunnel structural design are important issues in high-speed railway tunnel engineering. Accordingly, Bernoulli's principle, compressible N–S equations, one-dimensional pressure-wave theory, and isentropic compression are used to explain tunnel airflow at different levels. This study first analyzes the basic mechanisms of airflow pressure changes and the formation and propagation of pressure waves as a high-speed train enters a tunnel based on those theories. Then, it draws on relevant research from China and abroad to discuss methods for improving tunnel aerodynamic performance, including tunnel cross-sectional dimensions and blockage ratio, gradually varying portal structures, and perforated buffer and pressure-relief structures. The mechanisms and practical characteristics of these approaches are also compared, with the aim of providing a theoretical reference for the structural design and aerodynamic optimization of high-speed railway tunnels.

2. Fundamental theories and mechanisms of air pressure fluctuations

2.1. Physical principles and applicability constraints of Bernoulli's principle

In fluid mechanics, Bernoulli's principle provides a basic relationship between the velocity of a flow and its static pressure. For incompressible flow, the Bernoulli relation is normally applicable to steady,

frictionless motion along a streamline, particularly when the Mach number remains below approximately 0.3. The incompressible Bernoulli equation can be written as:

$$P + ½\rho v^2 + \rho g h = C \tag{1}$$

An increase in flow velocity corresponds to a decrease in static pressure, while a decrease in flow velocity leads to an increase in static pressure. As the operating speed of high-speed trains increases to 300–400 km/h, the characteristic Mach number approaches or even exceeds 0.3. In addition, the tunnel blockage effect further increases local air compression. Therefore, air compressibility can no longer be ignored, and air density is no longer constant, rendering the aforementioned equation inapplicable. For compressible adiabatic flow, the conserved quantity is no longer the sum of static and dynamic pressure, but the total enthalpy:

$$\mathrm{h_{tot}} = \mathrm{h} + \frac{12}{\mathrm{V}}^{2} \tag{2}$$

The conservation of total enthalpy further leads to the relationship of total temperature:

$$\mathrm{T_{tot}} = \mathrm{T}\left(1 + \frac{\gamma-1}{2}\,\mathrm{M}^2\right) \tag{3}$$

Under isentropic conditions, the total pressure remains constant. Once shock waves, friction, or turbulent dissipation occur, the flow becomes non-isentropic, resulting in total pressure loss and an increase in entropy. In this case, the simple Bernoulli principle no longer applies [4]. Despite these

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limitations, the classical Bernoulli equation is still widely used in the engineering analysis of high-speed railway tunnels. This is mainly because the Bernoulli principle provides an intuitive way to describe the basic energy relationship between flow velocity changes and static pressure. In local flow regions, when the air compressibility, viscous dissipation, and non-steady-state effects are relatively weak, the Bernoulli principle can be used to approximately or qualitatively assess the pressure changes caused by the acceleration or deceleration of the airflow.

When high-speed trains are in operation, especially when they enter a tunnel or when two trains are traveling towards each other within the tunnel, the flow field exhibits three-dimensional, unsteady, viscous, turbulent and compressible characteristics [5]. Compression waves and expansion waves propagate in the tunnel at speeds close to the speed of sound, while the air density and temperature change with pressure disturbances. These characteristics make the unsteady compressible Navier–Stokes equations the appropriate governing framework for describing the resulting flow field [4]. The energy equation uses the relationship between total enthalpy and total temperature to describe the conversion between internal energy and macroscopic kinetic energy. Although the full three-dimensional formulation provides a detailed description, solving it through CFD can require substantial computational resources. To analyze the basic mechanism more quickly, researchers, based on the geometric feature that the axial length of the tunnel is much greater than its cross-sectional hydraulic diameter, simplified the three-dimensional N-S equations, thereby obtaining a one-dimensional unsteady compressible pressure wave model [5].

2.2. One-dimensional pressure-wave propagation, transmission, and reflection theory

One-dimensional unsteady compressible pressure-wave model is a mechanism-based analytical approach derived by simplifying the three-dimensional compressible unsteady N–S equations according to the geometric characteristics of tunnels. Its main assumptions are that the axial length of the tunnel is much greater than its cross-sectional hydraulic diameter, pressure waves propagate mainly along the tunnel axis, and flow parameters such as pressure, velocity, and density are approximately uniform across each tunnel cross-section, while radial and circumferential flow gradients are neglected.

Once the rear of the train has passed into the tunnel, the newly available space behind the train produces an expansion disturbance. Both the compression wave and the expansion wave propagate along the axis of the tunnel at speeds close to the local sound speed [6]. A sudden change in tunnel geometry, such as an entrance, shaft, or branch connection, causes an incoming pressure wave to undergo both reflection and transmission. Some of the waves can be reflected and continue to propagate back and forth within the tunnel, while the remaining energy is transmitted through the opening to the external atmosphere [5, 7]. The tunnel exit is a typical open boundary: the incident compression wave will be reflected in the form of an expansion wave, and the incident expansion wave will be reflected in the form of a compression wave. Multiple wave systems repeatedly undergo reflection, superposition, and interference, resulting in intense transient pressure fluctuations within the tunnel [7-9]. These pressure disturbances trigger the aforementioned problems.

2.3. Isentropic compression theory and its applicability to tunnel flows

Isentropic compression is a fundamental concept in compressible gas dynamics. An isentropic process is defined as a reversible and adiabatic compression or expansion process, during which the

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entropy remains constant. The pressure, density, and temperature satisfy the following adiabatic relations:

$$P = C\,\gamma\,\rho \tag{4}$$

The isentropic compression model assumes no frictional dissipation, no heat transfer, and a completely reversible process. Under these ideal conditions, the total pressure, total enthalpy, and total temperature remain constant during the propagation of the pressure wave. Therefore, the isentropic compression theory becomes a fundamental tool for explaining the formation of compression waves and expansion waves [5, 8].

At the initial formation process of the compression wave described in Section 2.2, isentropic compression can explain the instantaneous changes in the gas state during the formation of the compression wave [10]. In the early studies of the Japanese Shinkansen, the wave generation process within a very short distance near the tunnel entrance was often approximated as an isentropic compression process. This method enabled the derivation of theoretical estimates for the initial compression wave amplitude, thereby providing a theoretical basis for studying the mechanism of the tunnel buffer structure [11].

However, the actual flow inside the tunnel does not fully conform to the ideal assumptions of an isentropic process. Factors such as viscous boundary layers, wall friction, nonlinear wave effects, local vortices, and weak heat transfer all contribute to entropy generation, causing the flow to deviate from the isentropic state. Under these conditions, if the flow is assumed to be adiabatic, the total pressure will significantly decrease, while the total temperature will remain largely unchanged [5]. The comparison between one-dimensional models and mobile model experiments indicates that if the isentropic assumption is applied throughout the tunnel, it will significantly overestimate the pressure wave amplitude and the pressure rise gradient. It will result in systematic differences between numerical predictions and experimental measurements. Moreover, the wall friction terms in both steady-state and transient conditions are important factors causing the flow to deviate from the isentropic conditions and thus cannot be ignored [12].

3. Structural optimization strategies for tunnel aerodynamic performance

3.1. Optimization of tunnel cross-sectional dimensions and blockage ratio

Once the train enters the tunnel, its body reduces the free cross-sectional area available for airflow, so the displaced air is primarily forced through the gap surrounding the train. Blockage ratio is defined here as the fraction of the tunnel cross-sectional area occupied by the train:

$$\beta = At/As \tag{5}$$

Where, At is the cross-sectional area of the train and As is the cross-sectional area of the tunnel. A higher blockage ratio means that less effective space is available for airflow around the train, resulting in stronger compression of the air ahead as the train enters the tunnel.

When the train cross-sectional area remains unchanged, appropriately increasing the tunnel clearance can reduce the blockage ratio and provide more space for the air displaced by the train, thereby attenuating rapid air compression. However, increasing the tunnel cross-sectional area also increases excavation volume and construction costs. In practical engineering design, a balance

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should be achieved among aerodynamic performance, structural safety, and construction cost, with an appropriate blockage ratio selected according to the operating speed [5, 7].

3.2. Optimization of gradually varying tunnel portals and buffer hoods

Compared with simply enlarging the entire tunnel cross-section, installing a buffer structure at the tunnel entrance is another important method for controlling the initial compression wave. When a high-speed train moves directly from an open environment into a conventional tunnel, the boundary conditions of the air ahead of the train change abruptly, which can generate an initial compression wave with a steep pressure rise. As this wave propagates through the tunnel, its front may undergo nonlinear steepening and eventually generate a micro-pressure wave at the tunnel exit.

A buffer hood essentially creates a transition zone between the open environment and the main tunnel, allowing the airflow boundary conditions to change gradually rather than abruptly. The intensity of the micro-pressure wave at the tunnel exit is primarily governed by the maximum pressure gradient at the compression-wave front when it reaches the exit, rather than simply by the absolute amplitude of the pressure wave. From an aerodynamic perspective, the main objective of tunnel entrance optimization should therefore shift from simply "reducing pressure" to "controlling the pressure rise gradient." For trains operating at higher speeds, longer gradually varying buffer hoods or buffer hoods with larger cross-sectional areas can be implemented so that the air compression caused by the train entering the tunnel occurs progressively over a longer distance [8].

3.3. Perforated buffer hoods and pressure-relief structures

The strength of the micro-pressure pulse at the exit is more closely related to the maximum pressure gradient of the arriving wave front than to its absolute pressure amplitude. The basic principle is that when the train pushes air into the tunnel, some of the compressed air can be released through the ventilation outlets to the outside, thereby reducing the pressure disturbance that would otherwise spread along the tunnel axis completely.

The maximum pressure gradient is influenced by factors such as the ratio of ventilation openings, the position of the openings, and the Mach number of the train. A further study indicates that there is an optimal range for the ventilation ratio, suggesting that larger openings do not necessarily lead to better aerodynamic performance. From the perspective of pressure wave propagation, this result can be explained by the reflection and transmission mechanisms discussed in Section 2. Therefore, a properly designed pressure release structure can change the propagation path of pressure waves and reduce the pressure gradient within the main tunnel. The position and size of the pressure release openings should take into account the train speed and the propagation characteristics of the pressure wave. The perforated buffer structure can release compressed air, thereby reducing the maximum pressure gradient [2].

Overall, the above three tunnel aerodynamic optimization measures function through different mechanisms: reducing the blockage ratio, smoothing the changes in the inlet boundary conditions, and guiding and releasing the compressed air. They have significant differences in their working principles, engineering costs, and application scopes. To facilitate the selection of solutions and parameter comparison during the engineering design process, this paper, based on the previous analysis and existing research results, compares the main characteristics of these three optimization methods. See Table 1 for details.

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Table 1. Comparison of the key characteristics of three tunnel aerodynamic optimization strategies

Optimization Strategy	Main Mechanism	Main Optimization Effects	Construction Cost	Typical Applications
Increasing Tunnel Clearance	Reducing the Blockage Ratio	Reducing Air Compression	High	New High-Speed Railway Tunnels
Gradually Varying Tunnel Portal	Smoothing Boundary Changes	Reducing the Pressure Gradient	Medium	High-Speed Railway Tunnel Portals
Perforated Buffer Hood	Airflow Diversion and Pressure Relief	Mitigating Micro-Pressure Waves	Medium	Tunnels with Significant Micro-Pressure Waves

4. Conclusion

This study analyzes airflow pressure changes and aerodynamic performance optimization during the entry of high-speed trains into tunnels from the perspectives of fluid mechanics and tunnel structural design. High-speed railway tunnel flows are essentially compressible, unsteady, and viscous. The classical incompressible Bernoulli equation can only provide a qualitative explanation of local flow behavior, while the compressible unsteady N–S equations and one-dimensional pressure-wave models provide a more appropriate description of the aerodynamic processes.

The findings further indicate that effective aerodynamic design should consider the rate of pressure increase at the compression-wave front, rather than evaluating wave amplitude alone. Tunnel clearance enlargement, gradually varying portals, and perforated buffer structures can respectively reduce the blockage effect, control the pressure rise gradient, and mitigate portal micro-pressure waves. Therefore, there is no single optimal tunnel structure that can be applied regardless of operating conditions. Their selection should instead reflect key conditions such as operating speed, blockage ratio, and tunnel length. This study mainly provides a comprehensive discussion based on theoretical analysis and existing research results, without conducting a unified quantitative comparison of different structural parameters. Future research can combine CFD simulation, scaled model tests and on-site monitoring data to systematically optimize key parameters, providing further guidance for the aerodynamic design of high-speed railway tunnels.

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